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Triggering of merger-induced starbursts by the tidal field of galaxy groups and clusters

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ABSTRACT

Star formation in galaxies is for a part driven by galaxy mergers. At low redshift, star formation activity is low in high-density environments like groups and clusters, and the star formation activity of galaxies increases with their isolation. This star formation – density relation is observed to be reversed at $z \sim 1$, which is not explained by theoretical models so far. We study the influence of the tidal field of a galaxy group or cluster on the star formation activity of merging galaxies, using N-body simulations including gas dynamics and star formation. We find that the merger-driven star formation is significantly more active in the vicinity of such cosmological structures compared to mergers in the field. The large-scale tidal field can thus enhance the activity of galaxies in dense cosmic structures, and should be particularly efficient at high redshift before quenching processes take effect in densest regions.

Key words: galaxies: evolution – galaxies : interactions – galaxies: starburst – galaxies: clusters: general

1 INTRODUCTION

In the Local Universe ($z \simeq 0$), the strongest starbursts occur in interacting systems; luminous and ultraluminous infrared galaxies are usually found in major mergers involving at least two galaxies of comparable masses (e.g., Duc et al. 1997). At redshift $z \simeq 1$ and above, an important fraction of starbursts still seem associated with interactions and mergers (Conselice et al. 2003; Bridge et al. 2007), even if the bulk of star formation may not be simply merger-driven (Bell et al. 2005; Daddi et al. 2007; Jogee et al. 2007). Theory and numerical simulations succeed in explaining the triggering of starbursts by galaxy interactions and mergers (e.g., Mihos & Hernquist 1996). However, supernovae feedback can regulate the star formation in mergers (Cox et al. 2006) and Di Matteo et al. (2007) showed from a statistical study of a large sample of galaxy interactions and mergers that the maximal star formation rate (SFR) in interacting galaxies is rarely higher than a few times that of isolated galaxies even in equal-mass mergers – the activity decreases significantly with increasing mass ratios (Cox et al. 2007). This suggests that some factors contributing to the triggering of high SFRs in mergers could have been neglected.

At low redshift, the star formation activity in a given galaxy is anti-correlated to the density of galaxies that surround it (Lewis et al. 2002; Kauffmann et al. 2004), galaxies in or near groups forming less stars than galaxies in poorer regions of the field. In clusters, star formation is even less active, which is explained by a variety of phenomena including the ram-pressure stripping (Quilis et al. 2000), galaxy harassment (Moore et al. 1996), and galaxy strangulation (Kawata & Mulchaey 2007).

Cosmological ΛCDM models (Millenium, Springel et al. 2005) explain the Local star formation activity – environmental density relation, but predict that it gets reversed only at very high redshift $z > 2$. Yet, it has been recently discovered that the star formation – density relation is already reversed at $z \simeq 1$, where the star formation activity of galaxies increases with the local density of the surrounding galaxies, except in the very densest regions (Elbaz et al. 2007, Cooper et al. 2007). This reversal of the star formation-density relation at $z \sim 1$ is theoretically unexplained by hierarchical models and cannot simply result from major mergers being more frequent in dense environments (see Elbaz et al. 2007). This suggests that unknown environmental mechanisms can trigger the star formation activity further than what mergers do. These environmental processes may still take place during mergers, at least for a part, since the later remain a major driver of star formation.

In this Letter, we study the influence of the tidal field of galaxy groups and clusters on the star formation activity of isolated and merging galaxies. While the tidal field of such structures alone only triggers a weak activity in a single galaxy, we show that it can strongly enhance the SFR of merger-induced starbursts. Mihos (2004) has shown that an external potential can modify the morphology of gaseous

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tidal tails developed in galaxy mergers, but did not study the star formation in this context. Here we show that galaxy mergers are statistically more efficient in triggering strong starbursts if they take place in the vicinity of a larger structure. This should contribute to the triggering of star formation in dense environments at $z \sim 1$. Indeed the triggering of star formation by the large-scale tidal field should be efficient in particular in young groups and near forming clusters, where the quenching factors did not have time to act yet. The numerical simulations are described in Section 2, and the results are presented in Section 3. Our conclusions are discussed and summarized in Sections 4 and 5.

2 NUMERICAL SIMULATIONS

2.1 Code and model description

Galaxies are modelled as stars, gas and dark matter particles. The gravitational potential is computed with an FFT-based particle-mesh technique, with a spatial resolution and softening of 190 pc, as described in Bournaud & Combes (2002, 2003). Gas dynamics is modelled with a sticky-particles scheme with parameters β_r=0.7 and β_t=0.5. Star formation is computed using a local Schmidt law : the star formation rate is proportional to the local gas density to the exponent 1.5 (Kennicutt 1998).

In order to directly compare the SFR of an interacting galaxy and of the same galaxy isolated, at fixed gas mass, we implement a gas disc of 10^5 particles in this galaxy, together with $7{\times}10^4$ stellar particles and $5{\times}10^4$ dark matter particles. The particle mass resolution is $1.5{\times}10^4$ $M_\odot$ for gas, $1.8{\times}10^5$ $M_\odot$ for stars, $10.8{\times}10^5$ $M_\odot$ for dark matter. The merging companion is modelled with $7{\times}10^4$ stellar particles and $5{\times}10^4$ dark matter particles. Because we study star formation mainly in a context of $z > 0$, we model galaxies with a moderate visible mass of 1.5×10^{10} $M_\odot$. At $z = 0$ this corresponds to somewhat small spirals (similar to M 33). The bulge:disc mass ratio is 0.24, the gas mass fraction in the disc is 15%. The bulge has a scale-length of 600 pc, the disc has a Toomre profile with a radial scale-length of 1.6 kpc for stars and 4.6 kpc for gas, truncated at 5.6 kpc. A dark halo of mass 5.4×10^{10} $M_\odot$ is implemented with a Plummer profile of scale-length 6 kpc truncated at 20 kpc, giving a circular velocity $V_{\rm circ} \simeq 100$ km s^{-1}.

Galaxies are evolved as isolated systems for 500 Myr before simulations are started. This way, galaxies already have acquired a realistic (barred) spiral structure when they interact and merge, without having time to undergo a major secular evolution of their bulge mass or disc size. Star formation is shut down during this initial period, so that interactions really start with the gas fraction indicated above. The evolution of the SFR is thus related to the interaction/merger, without any bias introduced by the transition from the initial axisymmetric model to a realistic spiral disc.

2.2 Galaxy mergers, group and cluster potential

We performed simulations of binary equal-mass mergers of two spiral galaxies corresponding to the model above. The orbital parameters of the merging pair are as follows:

- the inclination i of the orbital plane with respect to each galactic disc was fixed to 33 degrees. This is the average value $\int i\ p(i)\ di$, the probability of an inclination i being $p(i) \propto i$ in spherical geometry. This way we model typical orbits that are not coplanar nor polar.
- the initial velocity V was varied to 0.2, 0.4, 0.6 and 0.8, in units of the circular velocity $V_{\rm circ}$.
- the impact parameter b (defined as the initial separation in the direction perpendicular to the initial velocity) was varied to 3, 4, 5, and 6 times the gas disc radius.
- the orientation was varied to prograde and retrograde.

We model groups and clusters gravitational potential using a Plummer profile. This choice is discussed in Section 3.3, and should be representative of most groups and clusters tidal field at least in the peripheral regions studied here. The modelled cluster has a mass of 10^{15} $M_\odot$, and a radial scale-length of 400 kpc (this choice would be reasonably representative for instance of the Virgo cluster (e.g., Fouqué et al. 2001) and the group a mass of 5×10^{13} $M_\odot$ and a scale-length of 150 kpc, which could be representative of the Local Group depending on its dark:visible ratio.

The galaxy pair was initially placed at 400 kpc from the centre of the cluster (resp. 150 kpc from the group centre). Galaxies are not placed specifically in central regions, but in the periphery. This is a more general choice, and in the case of clusters it ensures that galaxies there can still contain gas reservoirs and form stars.

We chose four possible configurations for the relative position of the galaxy pair and the group or cluster:

- configuration 1: the group/cluster centre is in the orbital plane, along the axis supporting the initial relative velocity of the galaxy pair.
- configuration 2: the group/cluster centre is in the orbital plane, along the axis perpendicular to the initial relative velocity of the galaxy pair.
- configuration 3: the group/group centre is in the orbital plane, along the bisector of the two previous directions.
- configuration 4: the group/cluster centre is at 45 degrees from the orbital plane, with a projected position in the orbital plane similar to configuration 3.

Each orbital parameter for the merging galaxies has been simulated without any external field, and with the group and the cluster in each configuration; the total number of cases is then as large as 320. We restrict ourselves to cases leading to a merger, otherwise the parameter space to explore would be too large. We make the choice of the galaxy pair having no initial velocity w.r.t. the group/cluster (but free to move within in) as justified in Sect. 3.2.

3 RESULTS

In the following, 'relative SFR' refers to the SFR of a galaxy with a merging companion and/or a group or cluster tidal field, divided by the SFR of the same galaxy isolated. The starbursts are described with the maximum value of the relative SFR, i.e. $\mathrm{SFR}_{\rm peak}/\mathrm{SFR}_{\rm isol}$ on Fig. 2.

3.1 Single galaxy in a group/cluster tidal field

We show in Fig. 1 the evolution of the relative SFR for a single galaxy in the group and cluster tidal fields (without

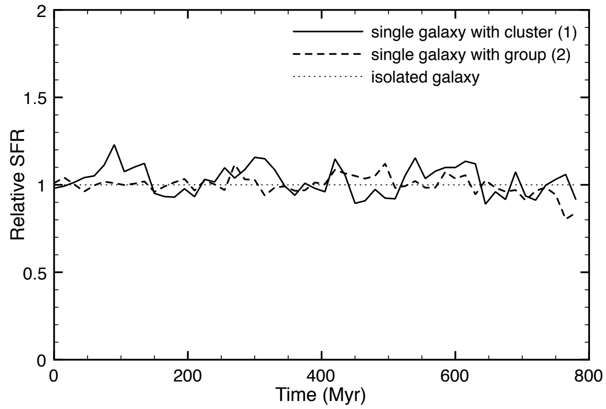

Figure 1. SFR of a single galaxy with a cluster in configuration 1 or a group in configuration 2, relative to the SFR of the same galaxy without the external field.

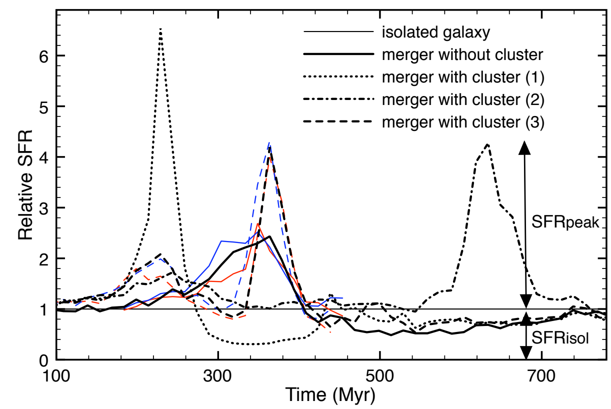

Figure 2. Comparison of the SFR (relative to the isolated case) for mergers without and with a cluster, in different configurations. Parameters are described in text (Sect. 3.2). The thin blue curves show SFR evolutions in the target galaxy when the perturbing galaxy also contains gas; the red curves show test simulations with a mass resolution of dark matter particles enhanced by a factor 3.

any interacting companion) for two of the simulated configurations. The average relative SFR is in both cases only slightly larger than 1. Thus, the tidal field of the cluster or the group can weakly trigger the star formation in a single galaxy, but without driving significant starbursts as mergers could do.

3.2 Merging pair in a group/cluster tidal field

The effect of the group or cluster tidal field on star formation can be larger when we replace the single galaxy by a merging pair. Before the systematical statistical study of Sect. 3.3, we show here an example of galaxy pair in the cluster field. Fig. 2 shows the relative SFR of a galaxy merging with an equal mass companion on a direct orbit with $V = 0.6V_{\mathrm{circ}}$ and $b = 4R_{\mathrm{disc}}$, with and without the cluster tidal field. The galaxy merger induces a starburst, the intensity of which is significantly affected by the cluster field: the peak intensity of the relative SFR is increased by the presence of the cluster, at various levels depending on the configuration. The triggering can be quite significant, with for example on Fig. 2 a peak SFR increased by a factor three when the cluster is in configuration 1, compared to the merging pair without the cluster field.

We tested in such simulations the influence of the initial velocity of the galaxy pair w.r.t the group/cluster, starting with radial and tangential velocities of 100 km.s^{-1} and 300 km.s^{-1}. The change in the SFR is found to be within five per cent. This weak influence justifies our choice to not vary systematically the initial velocity of the merging galaxy pair w.r.t the group/cluster.

3.3 Statistical analysis: star formation triggering

To perform a statistical analysis on our whole simulation sample, we take into account the fact that the various configurations leading to mergers that we simulated have different likelihoods, and must then be weighted accordingly. Within the simple assumption of a random distribution of companions, the collision rate varies as the velocity and the cross-section πb^2 for an impact parameter b. Thus, each simulation should be attributed a probability $\propto b^2 V f(V)$ (e.g., Mihos 2004) where $f(V)$ is the velocity distribution of galaxies. The distribution f is generally unknown. The real distribution $f(V)$ should increase with V (in particular in clusters, and for the moderate velocities leading to mergers that we study). In the following we present the results for $f(V) = 1$ and $f(V) \propto V$, assuming that the real distribution is likely in between. The variations caused by different assumptions on $f(V)$ are anyway small (see values below), and we mainly focus on the $f(V) = 1$ assumption that is found to give a conservative limit to the final result, the conclusions being quantitatively stronger (in minor proportions) if we assume an increasing form for f.

We show on Fig. 3 the statistical distribution of the maximum relative SFR ($\mathrm{SFR_{peak}/SFR_{isol}}$ on Fig. 2) for merging galaxy pairs with/without the external gravitational potential. We notice that the major mergers are significantly more efficient to trigger star formation if they take place in the gravitational field of a cluster or a group. Indeed, for a merging pair in the field, the fraction of 'significant' bursts (SFR multiplied by a factor 2 at least compared to the isolated reference disc) is 45% for $f(V) = 1$ (respectively 35% for $f(V) = V$). This fraction becomes 81% (resp. 85%) for the model group potential and 90% (resp. 92%) in the periphery of the model cluster. Similarly for 'strong' starbursts (say, SFR multiplied by at least a factor 5), only 6% (3%) of the mergers without any external potential reach this level, while this fraction is increased to 11% (21%) in a group tidal field as well as in a cluster tidal field. Thus, starbursts at all levels are triggered by the presence of the group/cluster potential: over our sample of mergers, the maximal instantaneous SFR is on average doubled, depending on the shape of $f(V)$, compared to mergers in the field far from groups and clusters. The enhancement is even larger in some cases, in particular for the highest initial velocities. This triggering effect is also important if we consider the integrated star formation over the burst duration (i.e. the total mass of stars formed) that is on average multiplied by 1.3–1.4 in the vicinity of both the model group and cluster.

We thus find a noticeable enhancement of the star for-

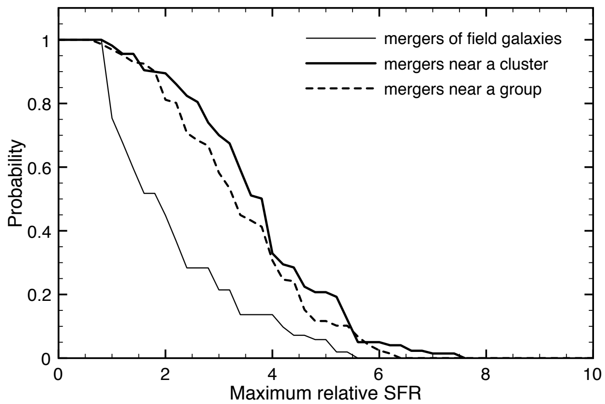

Figure 3. Probability to have a maximum relative SFR larger than the value specified on the x-axis for mergers of field galaxies vs galaxies in a group or cluster tidal field. The results shown are for the conservative assumption $f(V) = 1$.

mation activity resulting from the addition of the cluster or group potential. This effect is comparable in amplitude to the primary effect of star formation triggering by a major merger compared to an isolated galaxy, hence a significant one. Nevertheless the quantitative results are exact only for the adopted group or cluster mass, radius, and distance of the merging pair to the group/cluster centre. Other structures would be more or less efficient in triggering star formation depending on the intensity of their tidal field on the merging galaxies.

4 DISCUSSION

4.1 Modelling and numerical issues

We have assumed a Plummer profile for the potential of the modelled group and cluster. In the case of clusters, real potentials are more likely cuspy (Pointecouteau et al. 2005). A cuspy Hernquist profile with the same half-mass radius and total mass as our Plummer profile would actually exert a larger tidal field in its central regions near the cusp, and a comparable one (but always slightly larger) in the outer regions. The Plummer profile is thus a conservative choice, which could only lead to somewhat underestimating the effect. Changing the mass or scale-length of the structure by a factor two would lead to similar variations in its tidal field as changing its profile. Our choice was also motivated by the fact that forming groups and clusters at $z \sim 1$ are likely made-up of several merging sub-groups, with likely a large-scale profile flatter than relaxed structures. The halo profile of each galaxy might also be different from the one assumed in our model. This however should not have a major influence because the dark matter does not dominate the mass distribution in the central regions where the gas flows and star formation are triggered.

We chose to model the perturbing galaxy as gas-free, because merger-induced starbursts are mostly driven by gravity torques rather than hydrodynamical processes (e.g., Mihos & Hernquist 1996). Some test simulations (see examples on Fig. 2) confirm that the SFR evolution of the studied target galaxy is little influenced by the gas content of the perturbing galaxy even when the gas fraction in the latter is as high as in the former.

A sticky-particles code was employed to model the dynamics of the interstellar gas. The purpose is to provide a kinematically cold medium when the galaxy interaction occurs, but it is the response of the interstellar medium to the galaxy interaction that drives a gas inflow and subsequent starburst – not the sticky-particles dynamics. It takes several billion years for the angular momentum and energy of the ISM to vary significantly (see appendix in Bournaud & Combes 2002) and so the gas inflows and bursts of star formation are not largely dependent on the choice of this model and related parameters. We also note that our results on starbursts in merging pairs outside external potentials compare favourably to those obtained by Di Matteo et al. (2007) with an SPH model, and to the moderate SFR enhancement in mergers compared to non-interacting galaxies in GEMS (Jogee et al. 2007). Furthermore, a limited mass resolution of dark matter particles can induce N-body scattering, which can affect the structure of numerical merger remnants (e.g., Naab et al. 1999). We performed tests with a number of dark matter particles increased by factor three, which is found to leave the SFR evolution unaffected (Fig. 2).

4.2 Conditions for a star formation enhancement

Our results show that a given galaxy pair that merges in the vicinity of a group or cluster has an SFR enhanced by this external tidal field. In the statistical analysis, we have compared results assuming a similar velocity distribution for galaxies in the field and those near groups/clusters (either $f(V) = 1$ or $f(V) = V$ in all cases). This should be close to reality in groups, but one could expect higher velocities to dominate in the vicinity of clusters. Taking this into account would not however result in major changes; the average SFR enhancement is affected by 10% if we assume $f(V) = 1$ in the field and $f(V) = V$ near the cluster. One also expects an increase in the proportion of fly-bys not followed by mergers in the vicinity of clusters (not necessarily near groups). Di Matteo et al. (2007) showed that the SFRs are of the same order of magnitude for mergers and fly-bys, so that our results should be at first order extendable to higher-velocity fly-bys. When weighting our results with the cross-section πb^2, the impact parameter b was simply estimated at the beginning of our simulations ($t = 0$). The external tidal field would actually modify the orbits even before $t = 0$ and possibly bias this parameter b compared to the real impact parameter b_∞ at infinite distance. However, the difference between b and b_∞ is minimized when the group/cluster is in configuration 1 (along the direction of the initial velocity), and a significant enhancement of the SFR is still found when we restrict ourselves to this configuration (even 20% higher than in the other configurations). The star formation triggering that we found cannot then be an artefact resulting from the assimilation of b to b_∞.

The comparable effect found in our model group and model cluster indicates that the main requirement is the presence of a tidal field, while the total size and mass of the structure play only a secondary role in determining the exact level of triggering. One can however wonder if this really implies an observable triggering of the SF activity, because

the merging pairs in dense and low-density regions are not necessarily similar. Galaxies in groups can still contain important gas reservoirs, but galaxies in the central regions of relaxed clusters at $z \sim 0$ are mostly gas-depleted. The triggering effect of the large-scale tidal field should thus mainly affect galaxies in moderate density environments like groups, galaxies in the periphery of relaxed clusters but not at their centre, or in young/forming clusters where the quenching mechanisms did not have time to act yet. Galaxies in the periphery of clusters can indeed still have large gas reservoirs (Egami et al. 2006, see also Chung et al. 2007 for Virgo spirals). In the light of our results, we may then speculate that the specific SFR of galaxies (at least interacting ones) in the outer regions of clusters is higher than in both the field and the central cluster regions. Statistical comparison of the outskirts of clusters compared to the field and to the central cluster regions could confirm this prediction.

5 CONCLUSION

In this paper, we have shown that a major galaxy merger is more efficient to trigger an intense burst of star formation if it takes place in the tidal field of a galaxy group or cluster. While the group/cluster fields do not trigger much the star formation in a single galaxy, the effect on merging pairs is important. The starbursts in our simulations are amplified by a factor 2 on average (sometimes much more) for typical groups and clusters. More massive structures could even have larger quantitative effects depending on the intensity of the tidal field. A pair of M33-like spiral galaxies merging in the vicinity of a Local-like group or a Virgo-like cluster would see the intensity of its starburst amplified by the external field by typically a factor ~ 2, but possibly more on some orbits or regions of high tidal field. In a forthcoming paper, we will study the dynamical response of gas during mergers within such an external tidal field and the connection with the enhancement of starbursts.

Dense cosmological structures trigger the merger-induced star formation by the action of their tidal field. This holds at least from groups to clusters, the level depending on their mass and size. Because gas dynamics and star formation must be spatially well resolved for SFRs to be accurately computed in galaxy mergers , large-volume cosmological simulations may miss or underestimate this effect. This triggering of merger-induced starbursts by the tidal field of dense cosmological structures should be particularly efficient at high redshift ($z \simeq 1$ and above), when for instance the clusters begin to form and exert a tidal field, but are not virialized yet. Later on at $z \simeq 0$, quenching mechanisms have acted in the highest density regions resulting in a less active star formation there.

Our results unveil a new star-formation triggering mechanism in groups and at the periphery of clusters, which can act in particular at high redshift before star formation is quenched in dense regions. This can contribute to explain why LIRGs are often found in proto-cluster environments (Laag 2006) and the high frequency of blue star forming galaxies in young high-redshift clusters (Butcher & Oemler 1984). More generally, this can trigger the star formation activity in group mergers, and contribute to the reversal of the star formation – density relation with increasing redshift.

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